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MEASUREMENT OF INTENSE BEAMS OF THERMAL RADIATION

Research and Development Technical Report USNRDL-TR-35
NS 081 001

1 February 1955

by

A. Broido
A. B. Willoughby



U.S. NAVAL RADIOLOGICAL DEFENSE LABORATORY

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Subj: U. S. Naval Radiological Defense Laboratory Report USNRDL-TR-35;
forwarding of

Encl: (1) U. S. Naval Radiological Defense Laboratory Report USNRDL-TR-35
entitled "Measurement of Intense Beams of Thermal Radiation"

1. The subject report describes thermal radiation calorimeters constructed with relatively thick disks to permit the direct recording of integrated thermal energy received as a function of time. It is shown that, notwithstanding the use of a thick disk which permits measurement of high irradiance levels, the rate of change of recorded temperature can be made proportional to the rate of delivery of energy within a reasonably short time constant. Thus, differentiation of the recorded temperature data gives an accurate picture of the irradiance vs. time relationship.
2. These calorimeters have been successfully used, both in the laboratory and in the field, to measure, with a time constant of 20 milliseconds or less, radiant energy pulses up to 100 cal/sq cm with peak irradiances up to 200 cal/sq cm/sec.


R. A. HILMERS
Director

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Physics

Technical Objective
AW-7

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ABSTRACT

Thermal radiation calorimeters have been constructed with relatively thick receivers which permit the direct recording of integrated thermal energy dose as a function of time. However, it is shown that the rate of change of recorded temperature can be made proportional to the rate of delivery of energy within a reasonably short time constant. Thus, differentiation of the recorded temperature data will give an accurate picture of the irradiance-time history of an impinging pulse. Calorimeters have been successfully used, both in the laboratory and in the field, to measure, with a time constant of 20 milliseconds or less, radiant energy pulses up to 100 cal/sq cm with peak irradiances up to 200 cal/sq cm/sec.

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SUMMARY

The Problem

Instrumentation for measuring short, intense pulses of radiant energy in the visible and near visible portions of the spectrum was required in the research program concerning the effects of thermal radiation emitted during nuclear detonations. Additional requirements were that these instruments be small, rugged, and portable, and that their signals can be easily recorded directly on a high speed oscillographic recorder.

Findings

Thermal radiation calorimeters have been constructed with relatively thick disks to permit direct recording of integrated thermal energy received as a function of time. These calorimeters have been successfully used both in the laboratory and in the field.

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ADMINISTRATIVE INFORMATION

This is a report covering part of the work of the Armed Forces Special Weapons Project physical thermal program outlined in enclosures to COUSNRDL Conf. ltr 3-126-15 DAK: mey of 14 May 1953 to Chief AFSWP, subj: Proposed 1954 AFSWP Thermal Program, submission of. A more current version of this work has been described in "Outline of Planned USNRDL Technical Program, Fiscal Year 1955" (NRDL Secret Document Number 001085A, 16 July 1954) as AFSWP Project 1, Problem 1. This work has been previously reported under Technical Objective AW-7, Bureau of Ships Research and Development Project Number NS 081 001.

Acknowledgments

The authors gratefully acknowledge the assistance of members and associates of the Thermal Radiation Branch, USNRDL, in the design and extensive field testing of the calorimeter. Among those who contributed greatly are T. R. Broida, C. P. Butler, R. P. Day, R. W. Hillendahl, R. L. Hopton, R. M. Langer, F. I. Laughridge, J. R. Nichols and S. B. Martin.

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REPORT OF INVESTIGATION

1 INTRODUCTION

The prosecution of a program on the effects of thermal radiation emitted during nuclear detonations requires the development of instrumentation for measuring short, intense pulses of radiant energy in the visible and near visible portions of the spectrum. In particular, the thermal radiation program at the U. S. Naval Radiological Defense Laboratory required instruments for the field measurements of the radiant energy and power of the thermal pulses emitted during nuclear detonations, and similar measurements of intense thermal pulses produced in the Laboratory to simulate the field pulse. The requirements placed upon a satisfactory instrument were that it should measure, with a time constant of 20 milliseconds or less, radiant energy pulses up to 100 cal/sq cm with peak irradiances as high as 200 cal/sq cm/sec. Because of the difficulties encountered in field use and the desirability of minimizing complex electronic instrumentation in the field, additional requirements for a field instrument were that the instrument be small, rugged, and portable and that it provide a signal that could be recorded directly on a high speed oscillographic recorder.

Although instruments for the measurement of thermal radiation have been in use for many years, it is readily apparent that it would be difficult to find commercially available one instrument to meet all the requirements set forth above. Practically all available instruments are designed to work in the region below 0.01 cal/sq cm/sec and hence are not suited to the high irradiance levels under consideration. Further, the requirements of high energy levels and fast response times seem mutually exclusive since fast response times are generally achieved using thinner receiving surfaces which, in turn, would be destroyed by high level irradiation. The requirement of simplicity for field use tends further to eliminate systems which might otherwise be satisfactory.

A water-flow calorimeter¹ has been developed at USNRDL for use as a primary standard in the measurement of intense thermal radiation beams, but this instrument has a very long time constant and hence is not suitable for the measurement of short pulses of radiation. Secondary devices may,

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however, be calibrated against the water-flow instrument and then used for measuring the short pulses. Two distinct types of instrument have been designed and built to meet the needs set forth above. Both types of instrument utilize a blackened receiving surface with a thermocouple attached to the back of the receiver to measure the temperature to which the receiver rises. In each type of instrument a different artifice is used to obtain the desired response time and still prevent the receiver from melting down.

In one instrument, termed a calorimeter and described in detail in this report, a relatively thick receiver is used, so that the instrument has a long time constant in the usual sense and thus records the integrated energy as a function of time. However, it is shown that differentiation of the recorded temperature data will give an accurate picture of the irradiance-time history of a pulse within the required time constant. The other instrument, called a radiometer*, utilizes a very thin receiving disk with a corresponding short time constant. However, the edges of the receiving disk are placed in contact with a massive heat sink and thus the receiver is kept from melting down. In effect, the thermocouple measures the temperature difference between the center and edge of the receiving disk. This instrument records irradiance as a function of time, and, of course, this record may be integrated to give the results obtained directly with the calorimeter.

The validity of changing the thickness of the receiving disk to convert from an instrument which measures directly radiant energy densities (a calorimeter) to one which measures radiant power (a radiometer) may be seen from the following analysis. Consider the heat balance equation for an inert body subject to thermal radiation (the receiving disk). The rate of energy absorbed equals the rate of rise of heat content plus the rate of heat loss or

$$aAI = \frac{d\theta}{dt} MC + h(\theta - \theta_o) \quad (1)$$

where I = irradiance incident on the receiver in cal/sq cm/sec

θ = average temperature of receiver in degrees C

θ_o = ambient temperature in degrees C

* This instrument will be described in detail in a subsequent report. It is similar to the one described by Gardon, Review of Scientific Instruments, Vol. 24, No. 5, May 1953, pg. 366. The instruments used at this Laboratory were, in fact, modifications of the design suggested by Professor H.C. Hottel of the Massachusetts Institute of Technology. The principal modification involved the substitution of a silver foil for the constantan receiver. Because of the greater conductivity of silver, the internal dimensions could be increased considerably (thereby facilitating construction) without sacrifice of sensitivity or response time. Drift could be eliminated through the use of constantan wires run to the back of the heat sink as well as to the edge and center of the receiving disk. For Laboratory models, water cooling could be utilized also.

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t = time in sec

a = absorptivity of receiver

M = mass of receiver in gm

C = specific heat of receiver material in cal/gm/deg C

h = heat loss coefficient of receiver in cal/sec/deg C

A = irradiated area in sq cm

Assuming a constant irradiance I and assuming that h is independent of temperature, equation (1) can be solved to give

$$\theta = \theta_0 + \theta_o = \frac{aAI}{h} (1 - e^{-\lambda t}) \quad (2)$$

where $\lambda = \frac{h}{MC}$ = decay constant.

Now, if λ is made very large, so that for all times λt of interest λt is also very large, the exponential term can be neglected and equation (2) gives

$$\theta \sim I, \quad (3)$$

the ideal radiometer condition. On the other hand, if λ is made very small, so that for all times λt of interest λt is also very small, the exponential term can be approximated by $(1 - \lambda t)$ so that equation (2) gives

$$\theta \sim It, \quad (4)$$

the ideal calorimeter condition.

2 THEORY

2.1 Principles of Operation

The calorimeter consists, basically, of a metal plate receiver which is blackened on one side and has a thermocouple attached to the other side. Absorption of radiant energy by the blackened surface produces a

temperature increase in the plate, and this increase is measured by means of the thermocouple. Under conditions of uniform delivery of energy to the entire front surface of the receiver, the heat flow can be restricted to a direction perpendicular to the receiving surface. Therefore, at any instant the temperature at the rear surface of the plate can be obtained by a single thermocouple mounted at any point on the rear surface (usually the center).

The plate is kept sufficiently thin so that the temperature gradient across it is small and the back surface temperature may be used as an approximation to the average plate temperature. If, during the period of irradiation, the ideal calorimeter conditions apply and the heat losses are negligible (or if they are small enough to be corrected for), the back surface temperature at any time is a direct measure of the energy delivered up to that time and the rate of change of back surface temperature may be used to obtain the rate of delivery of energy. In order to determine the limitations of the foregoing theory and to obtain actual design criteria for the calorimeter, it is necessary to consider in some detail the effect of temperature gradients across the plate (i.e., the relationship between back surface temperature and mean temperature) and the effect of heat losses.

2.2 Temperature Gradients Across the Plate

Neglecting heat losses and assuming that the front surface of a plate of thickness L is uniformly irradiated so that heat flow takes place only in a direction perpendicular to the plate, the basic equation for heat flow in the plate is:

$$\frac{\partial \theta'}{\partial t} = K \frac{\partial^2 \theta'}{\partial x^2} \quad (5)$$

where $K = \frac{k}{PC}$ = thermal diffusivity

and P = density in gm/cm³

k = thermal conductivity in cal/sec/cm/deg C

The solution to equation (5) must fit the initial condition

when $t = 0$, $\theta' = \theta - \theta_0 = 0$

and the boundary conditions

where $x = 0$ (the back surface), $\frac{\partial \theta}{\partial x} = 0$

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and where $x = L$ (the front surface), $I = k \frac{\partial \theta}{\partial x}$

The solution² is

$$\theta = \frac{IL}{k} \left[\frac{Kt}{L^2} + \frac{3x^2 - L^2}{6L^2} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n e^{-Kn^2\pi^2 t/L^2}}{n^2} \cos \frac{n\pi x}{L} \right] \quad (6)$$

The back surface temperature, θ_b , is obtained by setting $x = 0$, thus

$$\theta_b = \frac{IL}{k} \left[\frac{Kt}{L^2} - \frac{1}{6} - \frac{2}{\pi^2} \sum_{n=1}^{\infty} \frac{(-1)^n e^{-Kn^2\pi^2 t/L^2}}{n^2} \right] \quad (7)$$

Differentiating, the rate of change of back surface temperature is obtained:

$$\frac{d\theta_b}{dt} = \frac{I}{CPL} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{-Kn^2\pi^2 t/L^2} \right] \quad (8)$$

Since $\frac{I}{CPL} = \frac{d\theta_m}{dt}$,

where θ_m is the mean plate temperature,

$$\frac{d\theta_b}{dt} = \frac{d\theta_m}{dt} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n e^{-Kn^2\pi^2 t/L^2} \right] \quad (9)$$

For reasonably small values of the exponential term in equation (9), the series converges sufficiently rapidly (due to the presence of the convergence factor n^2) to be approximated by the first term. Thus,

$$\frac{d\theta_b}{dt} \approx \frac{d\theta_m}{dt} (1 - 2e^{-K\pi^2 t/L^2}) \quad (10)$$

It can be seen that the expression in parentheses in this equation is similar to that in equation (2) except for the factor of two.

The time constant τ of an instrument whose response is given by equation (2) is defined as $\tau = \frac{1}{\lambda}$, i. e., it is the time necessary for the response of the instrument to reach $(1 - e^{-1})$ or 63 per cent of its final value. Because of the similarity of equations (2) and (10), the differentiated time constant τ' will be defined in a similar manner, i. e., as the time in which the rate of change of the back surface temperature reaches 63 per cent of its final value which is, of course, the rate of change of the mean plate temperature. Thus,

since $2e^{-1.7} = e^{-1}$,

$$\tau' = \frac{1.7}{\lambda'} = \frac{1.7L^2}{K\pi^2} = \frac{1.7L^2PC}{k\pi^2} \quad (11)$$

As long as the characteristics of the receiver are chosen so that τ' can be made less than 20 ms, the measure of the rate of change of back surface temperature presents a valid method of determining the rate of delivery of energy in so far as the time constant requirement is concerned.*

2.3 Heat Losses

For a calorimeter receiver of thickness L uniformly exposed to a constant irradiance I ,

$$\lambda = \frac{h}{MC} = \frac{h}{APCL} \quad (12)$$

and equation (2) may be written as:

$$\theta = \frac{aIt}{PCL} \left[1 - \frac{\lambda t}{2} + \frac{(\lambda t)^2}{6} - \dots \right] \quad (13)$$

The sensitivity S of the calorimeter may be defined as

$$S = \left[\frac{\theta}{It} \right]_{t \rightarrow 0} = \frac{a}{PCL} \quad (14)$$

In order to evaluate the effect upon the decay constant of the parameters in the denominator in equation (12), one must first consider the effect of these parameters upon the heat-loss coefficient h . This heat-loss coefficient is composed of three parts -- the radiative heat-loss coefficient, h_r , the convective heat-loss coefficient, h_v , and the conductive heat-loss coefficient, h_d . By restricting the temperature rise of the

* Prof. Horrel has pointed out that a somewhat shorter time constant may be obtained by utilizing the temperature at the thickness $x = 0.578L$, the thickness at which the temperature equals the mean temperature of the plate under equilibrium conditions.

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receiver to reasonably small values and by making the edge area of the receiver small with respect to the surface area, h may be made almost independent of the temperature and thickness of the receiver. Since h_r and h_v are both dependent upon A , a decrease in λ could be effected by increasing A only to the extent that h_d contributes to the total heat loss coefficient. Since h is essentially independent of L , a more effective method of decreasing λ is by increasing L . However, the thickness cannot be increased without limit because of the effect upon time constant [equation (11)] and because the sensitivity decreases with increasing thickness [equation (14)].

The characteristics of the optimum receiver material may be determined by eliminating thickness from the equations for the time constant, [equation (11)], the decay constant [equation (12)], and for the sensitivity [equation (14)]. Thus,

$$\tau' = \frac{1.7a^2}{k\pi^2 S^2 PC} = \frac{1.7h^2}{k\pi^2 A^2 \lambda^2 PC} \quad (15)$$

It may be seen that for given values of a and S , the minimum value of τ' is obtained by choosing the metal (copper) which has the largest value of kPC .

The upper thickness limit for a copper receiver may be calculated from equation (11) as

$$L \leq \left[\frac{k\pi^2 \tau'}{1.7PC} \right]^{\frac{1}{2}} \leq 0.36 \text{ cm} \quad (16)$$

An estimate of the thinnest receiver for which the heat losses may be neglected (say $\frac{\lambda t}{2} \leq 0.01$ for a pulse time of 10 sec. corresponding to $\lambda \leq 2 \times 10^{-3}$) may be made by assuming h_d to be negligible and h_v to be equal to h_r ; thus,

$$h = 2h_r = 4h'_r A \quad (17)$$

where h'_r is the radiative heat loss coefficient per unit radiating area.

Therefore,

$$L = \frac{h}{APC\lambda} = \frac{4h'_r}{PC\lambda} \quad (18)$$

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and for $\lambda \leq 2 \times 10^{-3}$

$$L \geq \frac{4h_r^4}{2 \times 10^{-3} \text{ PC}} \geq 2.4 \times 10^3 h_r^4 \quad (19)$$

The radiative heat-loss coefficient per unit radiating area may be calculated using the Stefan-Boltzman law. For a temperature rise of 100°C and assuming an emissivity of unity, h_r turns out to be 2.4×10^{-4} ; so

$$L \geq 2.4 \times 10^3 \times 2.4 \times 10^{-4} \geq 0.57 \text{ cm} \quad (20)$$

Since this calculation neglected h_d , the true lower limit of thickness would be somewhat greater than 0.57 cm .

Comparison of equations (16) and (20) indicates that the two conditions imposed upon L are not compatible, so that, in general, the heat losses may not be completely neglected. It may be shown, however, that all terms after $\frac{\lambda t}{2}$ in equation (13) may be neglected. The energy delivered to a calorimeter in the time t , therefore, is:

$$E = It \approx \frac{\theta_i}{S(1 - \frac{\lambda t}{2})} \quad (21)$$

and the rate of delivery of energy is

$$I \approx \frac{\theta_i}{tS(1 - \frac{\lambda t}{2})} \quad (22)$$

2.4 Determination of Variable Radiation

Equations (21) and (22) were derived for a pulse of constant irradiance. In cases of variable irradiation in which the pulse shape is known, equation (1) may be solved directly, utilizing the known function $I(t)$. However, for pulses in which the radiation is varying in an unknown manner, it is necessary to divide the total pulse time into small intervals in which the irradiation may be assumed constant. For these cases, the form of equations (21) and (22) may be derived by considering the i th time interval.

The temperature during the i th time interval is given by the solution of equation (1) with the initial conditions of $\theta_i = \theta_1$ and $t = 0$. Thus,

$$\theta_i = \frac{aIA}{h} (1 - e^{-\lambda t}) + \theta_1 (e^{-\lambda t}) = ItS (1 - \frac{\lambda t}{2}) + \theta_1 [1 - \lambda t + \frac{(\lambda t)^2}{2}] \quad (23)$$

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The energy ΔE_i delivered during the i^{th} time interval Δt_i is:

$$\Delta E_i = I_i \Delta t_i \approx \frac{(\theta_{i+1}^e - \theta_i^e)}{S} + \frac{(\theta_{i+1}^e + \theta_i^e)}{2} \frac{\lambda \Delta t_i}{S} \quad (24)$$

where I_i is the average irradiance during the i^{th} interval, θ_{i+1}^e is the temperature at the end of the i^{th} interval, and θ_i^e is the temperature at the beginning of the i^{th} interval. The total energy delivered to the end of the i^{th} interval is:

$$E_i = \sum_{j=1}^i \Delta E_j = \frac{\theta_{i+1}^e}{S} + \frac{\lambda}{S} \sum_{j=1}^i \frac{(\theta_{j+1}^e + \theta_j^e)}{2} \Delta t_j \quad (25)$$

As may be seen from this equation, the total energy is obtained by adding to the observed energy ($\frac{\theta_{i+1}^e}{S}$) the summation of the corrections for

each time interval. The shape of the thermal pulse is obtained by dividing the energy received during the i^{th} time interval by the duration of the i^{th} time interval, giving from equation (24):

$$I_i = \frac{\Delta E_i}{\Delta t_i} = \frac{(\theta_{i+1}^e - \theta_i^e)}{S \Delta t_i} + \frac{(\theta_{i+1}^e + \theta_i^e)}{2} \frac{\lambda}{S} \quad (26)$$

By use of equations (25) and (26) the total energy and irradiance-time shape of the thermal pulse may be calculated from the temperature-time curves of the calorimeter. The number of time intervals necessary to obtain the total energy with any degree of accuracy depends on the magnitude of λ and on the shape of the pulse. The number of intervals necessary to obtain a reasonably accurate value of irradiance is influenced, also, by the desired time resolution. As will be shown later, a compromise is sometimes necessary between the desired time resolution and the accuracy to which the value of irradiance during that time interval may be measured.

3. LABORATORY CALORIMETERS

3.1 Description

The first high-speed calorimeter developed for thermal measurements at this Laboratory was required for routine use with the 36-in.

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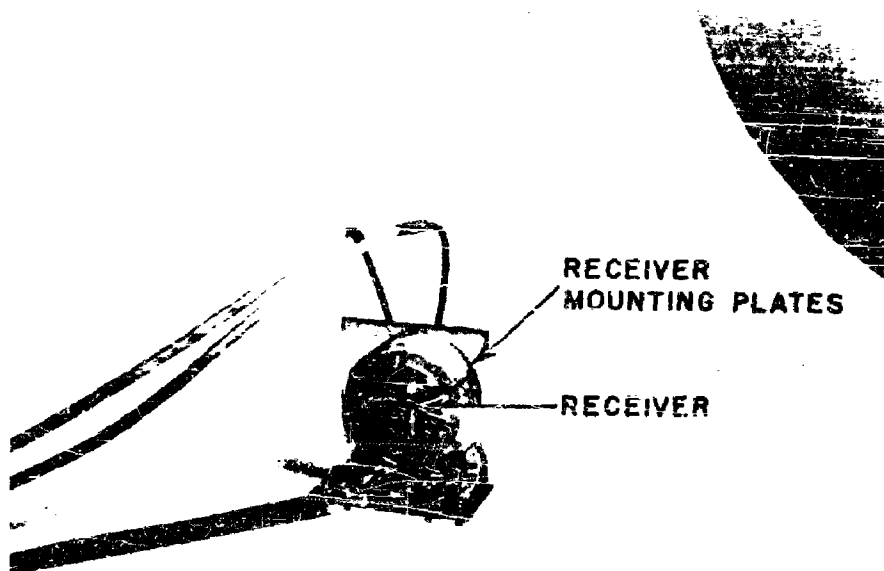


Fig. 1 Rear View of Mark IV Calorimeter Without Shielding Box

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searchlight thermal source.³ In this source, a nearly parallel beam from a Navy 36-in. searchlight falls on a second 36-in. paraboloidal mirror which focuses the radiation into an unmagnified image of the searchlight arc. The beam converges toward the focus in a cone of vertex angle of 120 deg. The image of the arc has a central cross-sectional area of 0.7 sq cm (a circle 1 cm in diameter) with an irradiance uniform within 10 per cent and with a maximum irradiance of about 100 sq cm/sec. For most applications, exposures are limited to this uniform area by means of a water-cooled aperture of 1 cm diameter.

If the carbon arc were a point source or small spherical source, the ideal shape of the receiver (in order for the heat flow to be one-dimensional) would be a spherical segment mounted in back of the center of the image of the arc, at a distance equal to the radius of curvature of the segment (R), the area of the segment being just large enough to intercept all the rays diverging from the focus. On the other hand, if the carbon arc were a small disk source (with diameter 1 cm), the ideal shape of the receiver would be a spherical segment located on a sphere passing through the circumference of the image of the disk source. If the radius of curvature of the segment were identical with the radius of the disk, the center of curvature of the segment would lie at the center of the arc image (as in the case of the point or spherical source). If the radius of curvature of the segment were considerably greater than the radius of the disk, the center of curvature of the segment would be a distance R back from the center of the image (towards the focusing mirror). Actually the arc acts like a combination of a spherical and disk source and the placement of the center of curvature depends on the magnitude of R .

The sensitivity of a calorimeter of this type mounted behind a limiting aperture may be varied either by a change in thickness of the receiver or by a change in the radius of curvature of the receiver. However, the thickness of the receiver also influences the response time of the instrument. In order to insure a sufficiently fast time constant, the thickness of the receiver was chosen as 0.1 cm. In order to produce a temperature rise of about 50°C under full beam conditions for 1 sec, the radius, then, was chosen to be 2.5 cm and, for this radius, the proper placement of the center of curvature was estimated to be about 0.5 cm back of the image.

The method of mounting the receiver in a laboratory calorimeter is shown in Fig. 1. The edge of the receiver rests on three tapered knife edges cut so as to provide proper centering in a Bakelite ring. The receiver is held against these knife edges by a second Bakelite ring which touches the receiver at only three points. The temperature of the receiver is measured by the 5 mil copper-constantan thermocouple soldered to the center of the rear surface. In the first design of this instrument (Mark IV)

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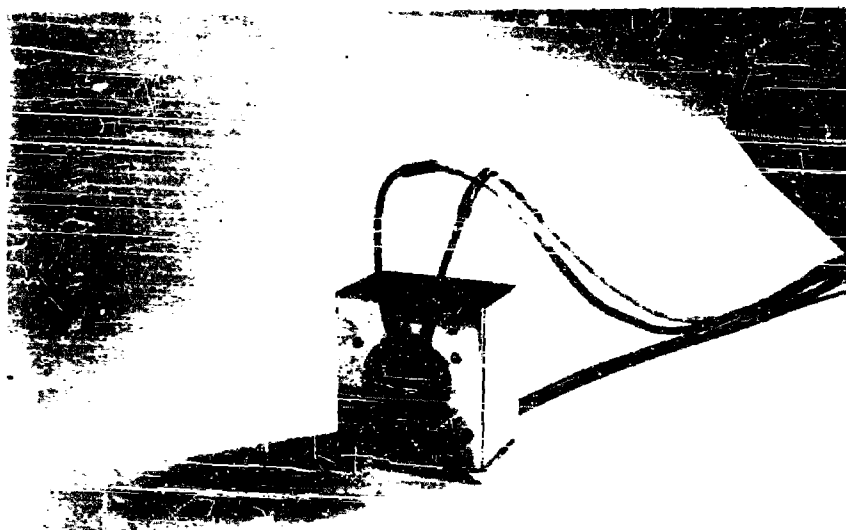


Fig. 2 Mark IV Calorimeter - Assembled

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the Bakelite rings were fastened directly to a water-cooled aperture (Fig. 2). In the final design (Mark VI), the aperture and calorimeter were made in two separate parts so that the aperture could be left in place at all times. In this way, experimental samples could be exposed behind the same aperture that was used for prior calorimetric measurements. Fig. 3 are photographs showing the Mark VI calorimeter.

3.2 Theoretical Constants

The sensitivity of the laboratory calorimeter as used with an external aperture may be defined as $S = \frac{aA}{MC}$ (27)

where A = aperture area.

Since the recording element of the instrument is a thermocouple, the data are recorded in terms of voltage rather than in terms of temperature. Consequently, a calibration constant for the instrument may be defined as:

$$B = \frac{1}{Se} = \frac{MC}{aAe} \quad (28)$$

where e = thermoelectric power of the copper-constantan thermocouple. Since both C and e are to some extent temperature dependent, B is not strictly a constant. Fortunately, however, the variations with temperature of C and e are in the same direction and tend to cancel each other. Thus, for the limited temperature range of use of these instruments (20°C to 90°C) an average value of C and e may be used, and the resulting average value of B represents a close approximation to the actual value of B anywhere within this range of temperature.

Table 1 gives the values of each of the factors entering into equation (28).

TABLE 1
Data for Calculation of Theoretical Calorimeter Constants

	Mark IV	Mark VI
Aperture area A (cm ²)	0.758 ± 0.003	0.705 ± 0.003
Receiver Mass M (gm)	16.1 ± 0.1	17.1 ± 0.1
Thermoelectric power e (μV/°C)	41.5 ± 0.8	41.5 ± 0.8
Specific heat C (cal/gm/°C)	0.0925 ± 0.0014	0.0925 ± 0.0014
Receiver absorptivity, a	0.975 ± 0.01	0.975 ± 0.01

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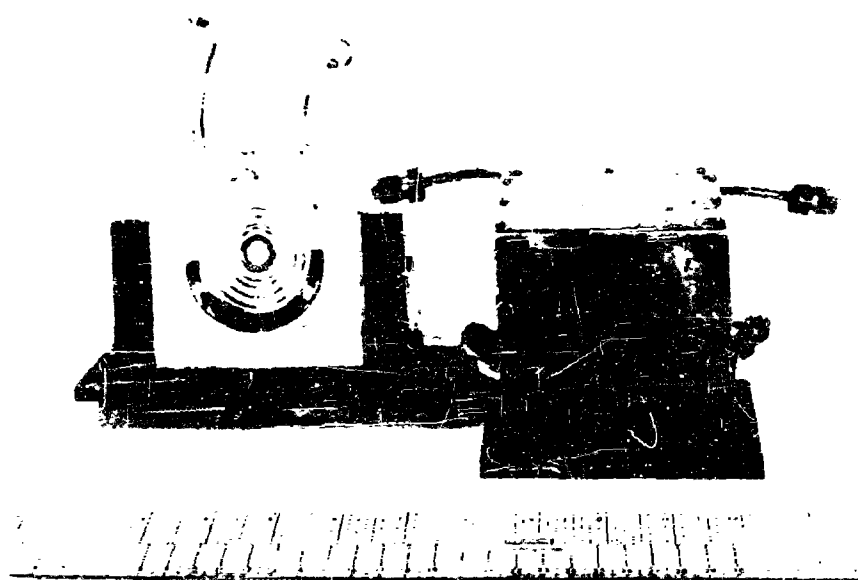


Fig. 3 View of Aperture and Mark VI Calorimeter

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The aperture areas were determined by use of a comparator; the receiver masses, by weighing; the thermoelectric power by comparison with an accurate thermometer, the absorptivity by measuring the diffuse reflectivity of a similarly blackened flat piece of copper in a Cary spectrophotometer; and the specific heat by values given in the literature for 20°C to 100°C. The theoretical calibration constants for the two calorimeters using the data given above are:

$$B_{IV} = 0.0487 \pm 0.0014 \text{ cal/cm}^2/\mu\text{V and}$$

$$B_{VI} = 0.0555 \pm 0.0016 \text{ cal/cm}^2/\mu\text{V}$$

The errors shown are the r.m.s. errors calculated from the individual uncertainties shown in Table 1.

The theoretical differentiated time constants may be calculated from equation (11) as:

$$\tau'_{IV} = \tau'_{VI} = 1.6 \text{ msec}$$

The average decay constant for the two instruments may be calculated from equations (12) and (17). Thus,

$$\lambda = \frac{h}{MC} = \frac{4h'A}{MC}$$

For a temperature rise of 50°C above ambient this equation yields

$$\lambda = 0.9 \text{ sec}^{-1}.$$

3.3 Experimental Evaluation

Because of uncertainties in some of the factors used in calculating the calibration factors, differentiated time constants, and decay constants for the Mark IV and the Mark VI calorimeters, these quantities were also evaluated experimentally. The experimental calibration factors were obtained by comparison with the water-flow calorimeter¹ using the 36-in. searchlight source. The thermocouple output of the calorimeters was recorded on a Heiland Oscillographic Recorder of the type used by this Laboratory for all calorimetric and radiometric field measurements. In this recorder a pencil of light about 0.2 mm wide is directed upon a continuously moving strip of photographic paper by reflection from a mirror fastened to the moving coil of a small D'Arsonval galvanometer. The results of the comparison are given in Table 2. The agreement between the theoretical and the experimental calibration factors is very good.

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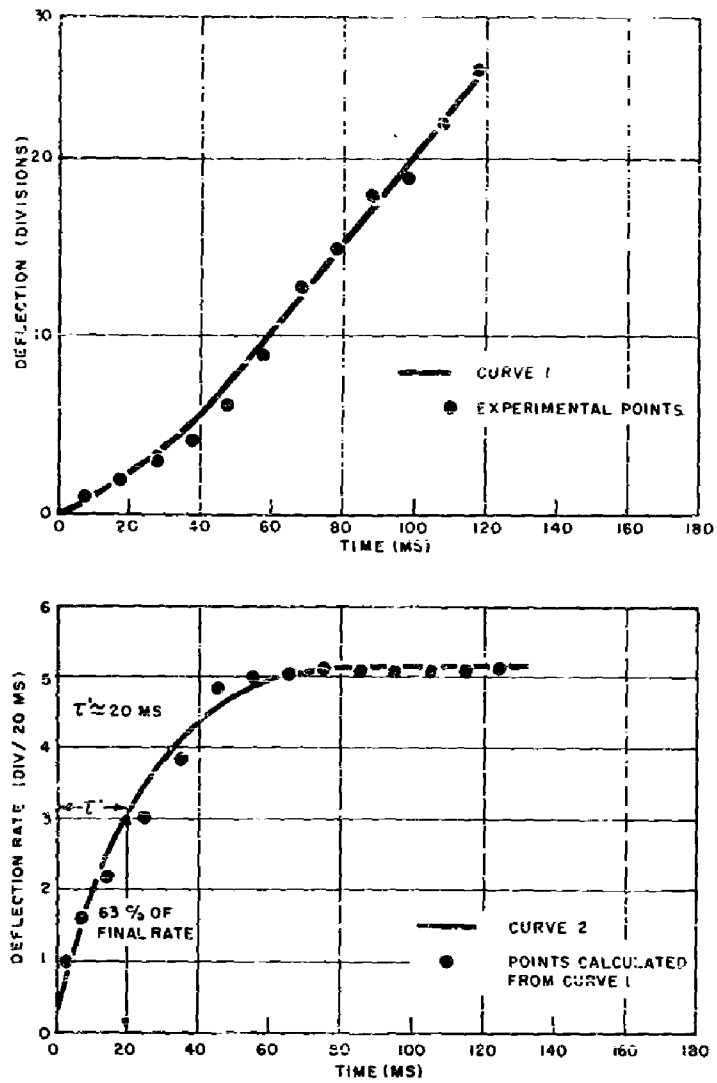


Fig. 4 Recorded and Differentiated Curve With Calorimeter Exposed to Constant Irradiance

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TABLE 2

Comparison of Mark IV and Mark VI Theoretical and Experimental Calibration Constants

Run No.	Experimental Calibration Constant (cal/cm ² /μV)	
	Mark IV	Mark VI
1	0.0483	0.0570
2	0.0479	0.0548
3	0.0461	0.0535
4	0.0494	0.0576
5	0.0494	0.0584
6	0.0501	0.0576
	0.0485 ± 0.0006 (S.D.)	0.0565 ± 0.0008 (S.D.)
Theoretical Constants	0.0487	0.0555

The time constants of the instruments were measured experimentally using the 36-in. searchlight source and its associated high speed air-driven shutter.³ Although the theoretical time constant of the calorimeter receiver was calculated to be 1.6 ms, the actual time constant of the instrument would be somewhat larger due to the mass of the thermocouple wire and solder on the rear surface of the receiver and to the small amount of sideways heat flow because of the non-ideal matching of thermal beam and receiver geometry. The time response of the entire system, including the shutter and galvanometer, would be greater yet. However, since the shortest time response needed was about 20 ms, it was deemed sufficient to show that the experimental value was less than this number. Curve 1 of Fig. 4 shows a typical curve recorded when the shutter is opened with one of the calorimeters in the focus of the searchlight source. Curve 2 of Fig. 4 represents the curve that may be obtained by the differentiation of Curve 1.

The decay constants of the two instruments were determined by plotting, as a function of time, the log of the ratio of the temperature at any time to the temperature immediately after stopping an exposure (zero time). The values obtained from the curves shown in Fig. 5, and the results are given in Table 3. The agreement between the experimental and theoretical values is fairly good considering the rough nature of the theoretical calculations.

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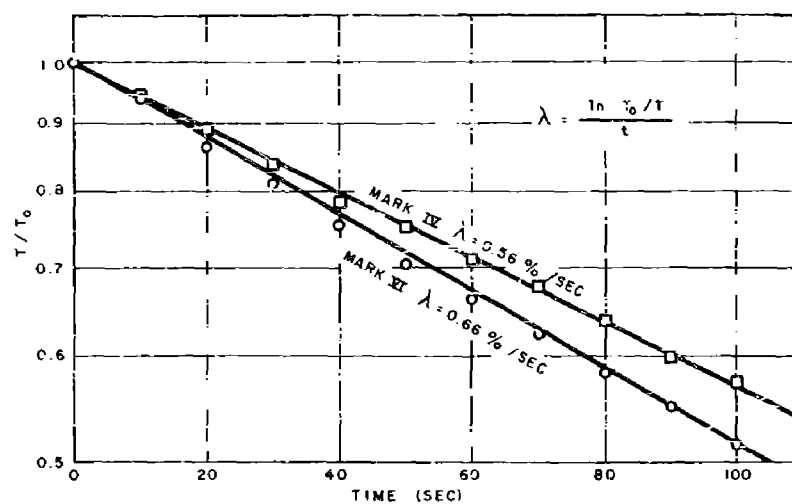


Fig. 5 Thermal Decay Curves for Mark IV and Mark VI Calorimeters

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TABLE 3

Comparison of Mark IV and Mark VI Theoretical
and Experimental Decay Constants

	Decay Constant (%/sec)	
	Mark IV	Mark VI
Experimental	0.56	0.66
Theoretical	0.90	0.90

4 FIELD (DISK) CALORIMETERS

4.1 Description

The second basic calorimeter design was required for field use in a nearly parallel beam of essentially unlimited extent and of uniform cross-section. The ideal shape of a receiver for measuring this type of beam, of course, is a flat plate. Since it was considered necessary to calibrate the instruments in the laboratory with the 36-in. searchlight source prior to field use, the surface area of the receiver was limited to a disk 1 cm in diameter. Depending upon the total energy that the instruments were expected to measure, the thickness of the receiver disk was selected in the range 0.05 to 0.32 cm. As with the laboratory calorimeters, the front surface of the receiver was blackened with electrolytically deposited platinum, finished coated with camphor black. Although the external features of the field calorimeters used by this laboratory changed from time to time, the basic design of the instrument did not change and all field calorimeters had the following characteristics in common.

In order to minimize conductive heat losses, all receiving disks were side mounted on needle points. The receiving disks are exposed through a quartz or other appropriate filter in back of an aperture which is provided to shield the other parts of the instrument. (No limiting aperture is needed for a flat receiver in a nearly parallel beam of radiant energy since the receiver itself limits the amount of energy it receives). In general, the aperture was made to accept radiation falling within a cone of 90° vertex angle. Except in the case of the thickest disk, a thermocouple consisting of 5 mil copper and constantan wires is soldered to the center of the

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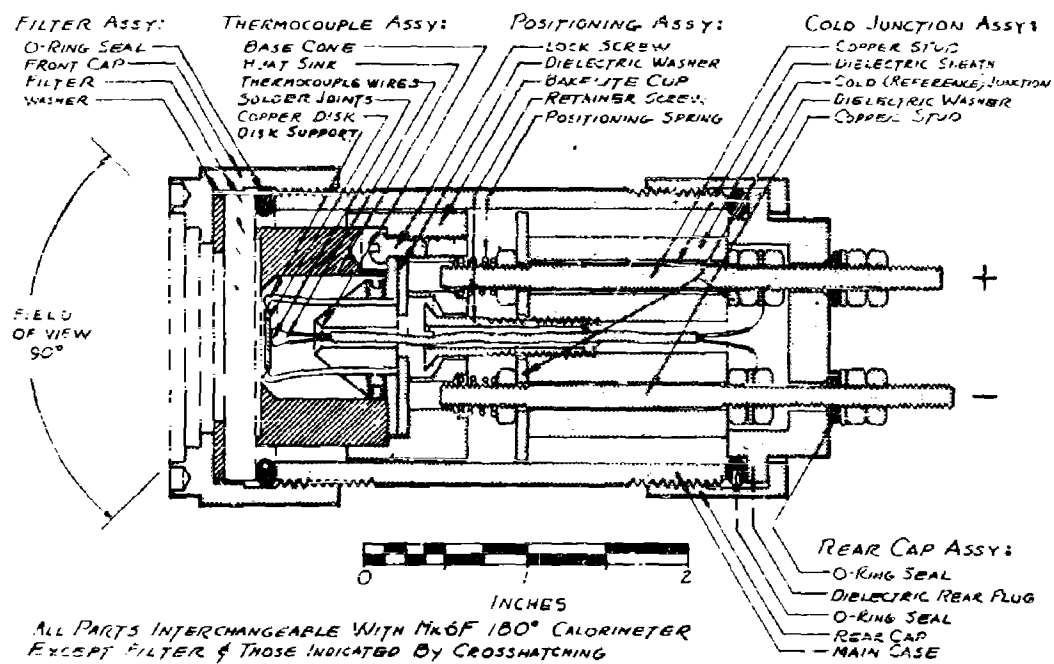


Fig. 6 Sketch of Mark 6F Field Calorimeter

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unblackened face of the disk. The other end of the thermocouple wire is fastened to the reference junction comprised of massive copper blocks housed in the calorimeter case. The electrical signal generated by the thermocouple is fed in to one galvanometer of a multi-channel oscillographic recorder. The basic design of the field calorimeter is shown in Fig. 6.

4.2 Theoretical Constants

As stated previously, one of the requirements for a satisfactory calorimeter was that the output signal be large enough to record directly on a portable oscillographic recorder. The recorder selected for field use was a Heiland Oscillographic Recorder Type A 500R. With this recorder the most sensitive galvanometer available with a time response faster than 20 ms has the sensitivity of 118.7 mm per milliampere. Since the optimum damping resistance (60 per cent of critical damping) for this galvanometer is 10.8 ohms, the corresponding voltage sensitivity is 6.35 mm per millivolt.

It has been found that a total deflection approximating 3 cm is necessary in order to get sufficient accuracy on differentiating the recorded trace. This deflection corresponds to a thermocouple output of 4.7 millivolts, which, for the thermocouples used, corresponds to a temperature rise of approximately 100°C. Such a temperature increase is too large for the assumption of constant calibration factor and decay constant to be valid. The change in decay constant is due primarily to the change in the radiative heat loss coefficient, as it may no longer be assumed that the radiative losses are proportional to the first power of the temperature. However, a curve of decay constant as a function of temperature may be determined experimentally over the appropriate temperature range and used in the analysis of recorded data.

As in the case of the laboratory calorimeter, the change in calibration factor is due to the change in thermoelectric power of the thermocouple and to the change in specific heat of the receiver. For a copper-constantan thermocouple mounted on a copper disk, the quantity $\frac{C}{e}$ may be expressed in terms of the thermocouple output as:

$$\frac{C}{e} = 2.359 - 0.034V - \frac{0.009}{V} \quad (29)$$

where V = output of the thermocouple junction with respect to a junction at 0°C.

This equation is accurate to 1% in the range $-40^{\circ}\text{C} < T < +190^{\circ}\text{C}$. The calibration factor may, therefore, be represented by the following equation:

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$$B = \frac{MC}{aAe} = M' \frac{C}{e} = M' (2.359 - 0.034V - \frac{0.009}{V}) \quad (30)$$

In this equation $M' = \frac{M}{aA}$ may be considered a thermal calibration constant which must be determined separately for each receiver, while the term within the parentheses applies to all receivers constructed of the same materials.

As in the case of the laboratory calorimeters, the differentiated time constant for the field instrument may be calculated from equation (11).

4.3 Experimental Evaluation

The calibration factors, time constants, and decay constants for the field instruments were determined in the laboratory in the same manner as were the constants for the laboratory calorimeters. In the determination of the calibration factors, the field instruments were compared directly with the Mark VI calorimeter which had previously been calibrated against the water-flow instrument. Representative values, both theoretical and experimental, for the various receiver thicknesses used are given in Table 4. In this table, column 2 gives the energy to which the receiver must be exposed to attain a temperature 100°C above ambient and give a trace deflection in the recorder circuit of about 3 cm. Both theoretical and experimental values for time constants, calibration factors, and decay constants are given for the temperature rise of 100°C.

TABLE 4

Theoretical and Experimental Constants for Representative Field Calorimeters

Thickness (in.)	Energy for 100°C Temp. Rise (cal/sq cm)	Time Constant (msec)		Calibration Factor (cal/sq cm)		Decay Constant (%/sec)	
		Theor.	Exp.	Theor.	Exp.	Theor.	Exp.
0.125	27	16	16	6.05	5.74	0.9	0.7
0.0625	13	4	4	3.20	3.23	1.8	1.5
0.0312	6.7	1	4	1.55	1.49	3.7	3.4
0.025	5.4	0.6	-	1.14	1.16	4.6	4.5
0.020	4.3	0.4	4	0.98	0.98	5.8	6.0

4.4 Use With a Variable Pulse

Since the method of analysis of pulses of variable radiation is to break down the total pulse time into small time intervals, the use of curves of calibration factor vs temperature and decay constant vs temperature does not introduce much additional effort. Thus, for example, equation (24) may be rewritten as:

$$\Delta E_i = \frac{(\theta_{i+1}' - \theta_i')}{S_i} + \left[\frac{(\theta_{i+1}' + \theta_i')}{2} \frac{\lambda_i \Delta t_i}{S_i} \right] \quad (31)$$

Where S_i and λ_i are, respectively, the sensitivity and decay constant corresponding to the temperature existing during the i^{th} interval.

In the field, the disk calorimeters have been used to determine the pulse of thermal radiation emitted during a nuclear detonation. The pulse shapes of interest are similar to the one given in Fig. 7. For such a pulse, a typical disk calorimeter would record a trace like that represented by the solid line in Fig. 8. The appropriate decay constants for the instrument could be obtained from the later portions of this curve and using these decay constants, the curve could be corrected as shown by the broken curve to give an accurate representation of the actual time variation of the energy delivered to the instrument.

Exact differentiation of the broken curve would, therefore, give the curve of irradiance vs time shown in Fig. 7. This differentiation may be accomplished approximately by reading for a short time interval Δt the energy Δq recorded during that interval and plotting the average irradiance for the time interval, $\frac{\Delta q}{\Delta t}$, as a close approximation to the true irradiance $\frac{dq}{dt}$. Depending upon the information desired, the differentiation techniques may be carried out in one of two ways. The difference between the two techniques depends upon the fact that the errors in reading the calorimeter traces are two types: (1) a calibration or scale error, which is a constant percentage regardless of the magnitude of the deflection, and (2) a reading error, which is constant in value and thus varies percentage-wise with the magnitude of the deflection.

The difference in the two techniques may be illustrated by taking as a typical case, a trace with a total deflection of 3 cm, which, for the pulse shape given in Fig. 7, would have at peak irradiance a peak deflection rate of about 6 cm/sec falling off at 2 sec to about 2-1/2 per cent of that value. It has been established that, with the techniques used in this Laboratory, the error in reading a good galvanometer trace is not greater than ± 0.003 cm. The reading error for the total energy measurement then is 3 ± 0.003 or 0.1 per cent, a negligible value.

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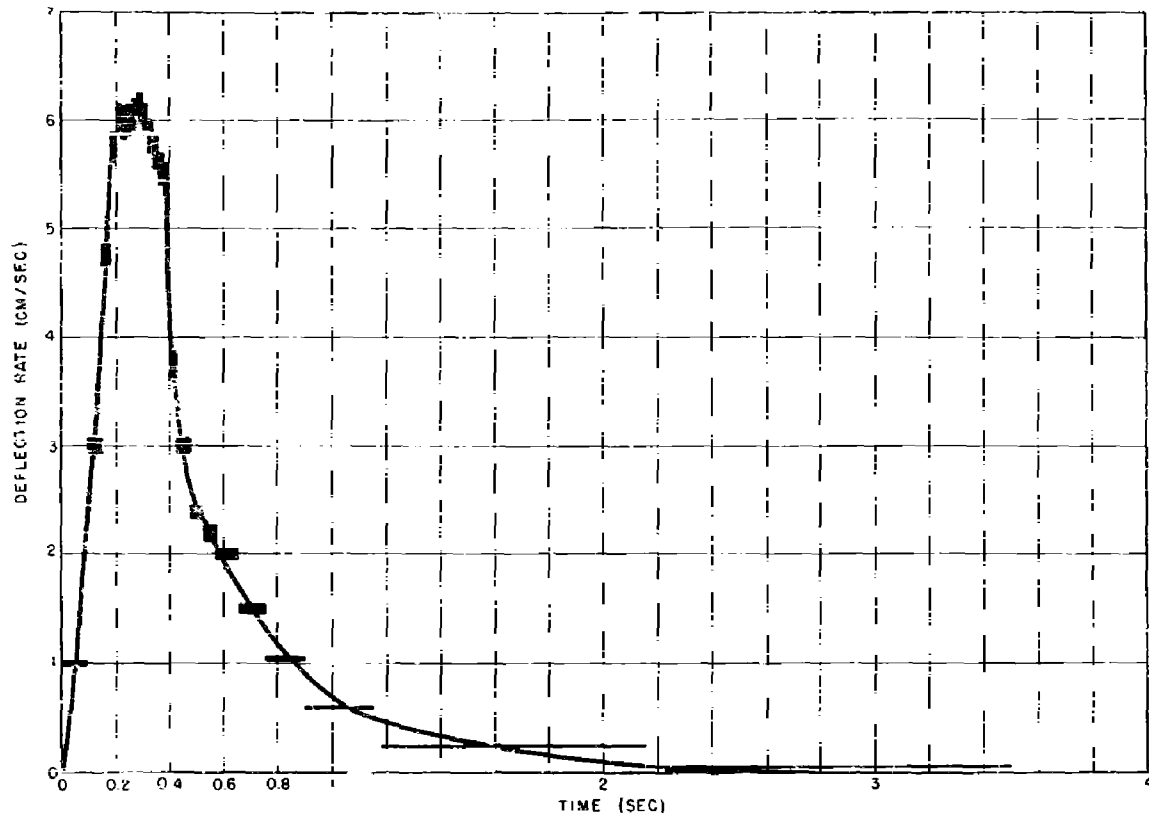


Fig. 7 Representative Field Pulse Shape

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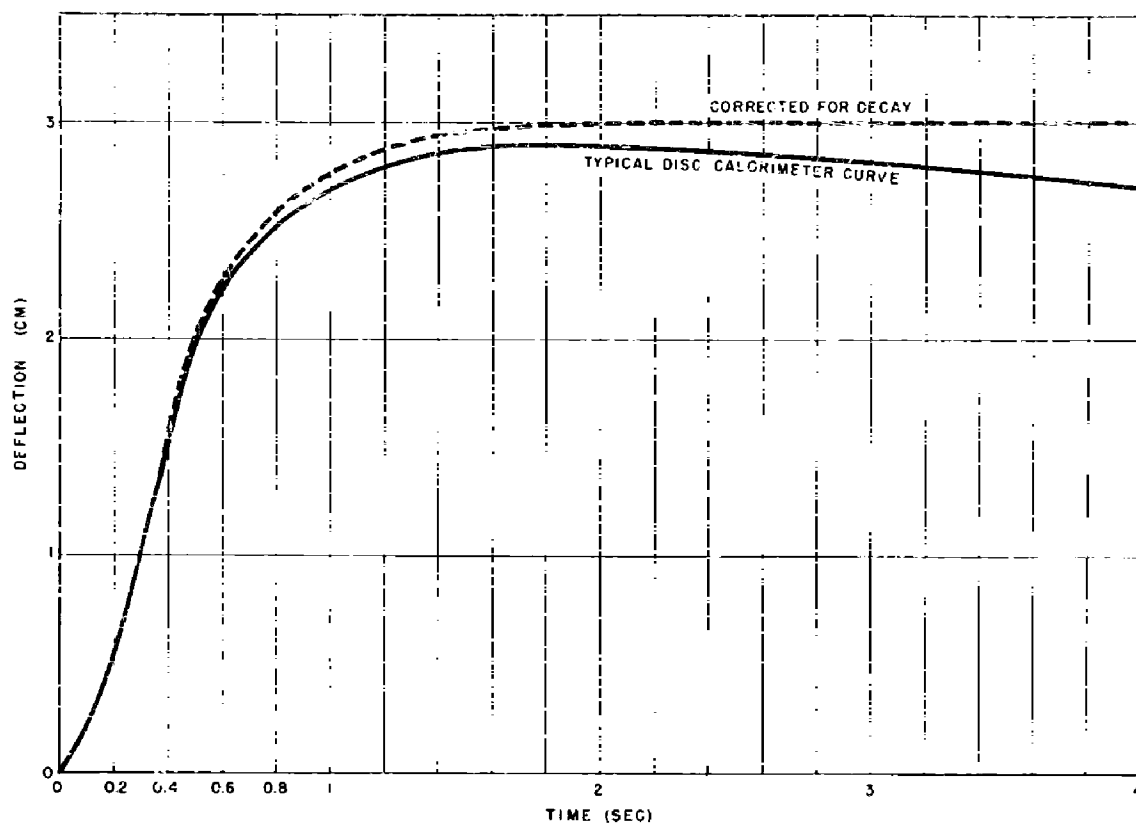


Fig. 8 Representative Integrated Energy-time Curve

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However, as a time resolution of 20 ms is desired, the irradiance curve must be based upon the deflection of the galvanometer during the 20 ms interval. At peak irradiance the error in this deflection would amount to $6 \text{ cm/sec} \times 0.02 \text{ sec} = 0.12 \text{ cm}$, and this value would be known to $\pm 0.003 \text{ cm}$, an error of ± 2.5 per cent. However, at 2 sec the deflection during the 20 ms interval would be only 0.003 cm and the uncertainty, then, would be equal in magnitude to the deflection itself.

If one restricts the need for a 20 ms time resolution to the interval around the peak irradiance, it is possible by proper selection of t to maintain a fixed percentage error in the irradiance value. Thus, if time intervals are chosen so as to maintain the energy interval found at peak irradiance, 0.12 cm in the example above, the uncertainty in the energy for the time interval will remain constant and thus the uncertainty in the irradiance will remain constant. This procedure gives the average irradiance fairly accurately for the time interval over which the measurement is made.

In obtaining irradiance-time curves, rectangles representing the time interval selected and the corresponding error in the irradiance for each point may be plotted rather than the point itself. As may be seen from Fig. 7, this procedure has the added advantage of having the long axis of the rectangle of uncertainty lie parallel to the curve in regions of slowly changing slope, thus simplifying the drawing of the curve.

SUMMARY

The calorimeters described in this report were designed to measure, with a time constant of 20 milliseconds or less, radiant energy pulses up to 100 cal/sq cm with peak irradiances as high as 200 cal/sq cm/sec. Each instrument consists, basically, of a metal receiver which is blackened on one side and has a thermocouple attached to the center of the other side. Absorption of radiant energy by the blackened surface produces a temperature increase in the receiver and this increase is measured by means of the thermocouple. The receivers are relatively thick, so that the instrument has a long time constant in the usual sense and this records the integrated energy as a function of time. However, it is shown that with proper receiver design, the rate of change of temperature at the thermocouple can be made proportional to the rate of delivery of energy within the required time constant, and thus differentiation of the recorded temperature data will give an accurate picture of the irradiance-time history of an impinging pulse.

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Several hundred calorimeters of the type described have been constructed. The instruments have been in routine use, both in the laboratory and in the field, for several years, and have performed satisfactorily in all respects. Their primary advantages are that they are small, simple, rugged, and that they provide a signal which may be recorded without complex amplification equipment directly on a high speed oscillographic recorder.

Approved by:

A. Guthrie

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Nucleonics Division

For the Scientific Director

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<p>Naval Radiological Defense Laboratory USNRDL-TR-35</p> <p>MEASUREMENT OF INTENSE BEAMS OF THERMAL RADIATION, by A. Broido and A. B. Willoughby. 1 Feb. 1955. vi, 34 p., illus, tables, diagrs.</p> <p>Thermal radiation calorimeters have been constructed with relatively thick receivers which permit the direct recording of integrated thermal energy dose as a function of time. However, it is shown that the rate of change of recorded temperature can be made proportional to the rate of delivery of energy within a reasonably short time constant. Thus,</p> <p>(over)</p>	<p>1. Thermal radiation - Measurement I. Broido, A. II. Willoughby, A. B. III. Title IV. NS 081 001</p> <p>UNCLASSIFIED</p>	<p>Naval Radiological Defense Laboratory USNRDL-TR-35</p> <p>MEASUREMENT OF INTENSE BEAMS OF THERMAL RADIATION, by A. Broido and A. B. Willoughby. 1 Feb. 1955. vi, 34 p., illus, tables, diagrs.</p> <p>Thermal radiation calorimeters have been constructed with relatively thick receivers which permit the direct recording of integrated thermal energy dose as a function of time. However, it is shown that the rate of change of recorded temperature can be made proportional to the rate of delivery of energy within a reasonably short time constant. Thus,</p> <p>(over)</p>	<p>1. Thermal radiation - Measurement I. Broido, A. II. Willoughby, A. B. III. Title IV. NS 081 001</p> <p>UNCLASSIFIED</p>
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Armed Services Technical Information Agency

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28 April 1997

MEMORANDUM FOR DEFENSE TECHNICAL INFORMATION CENTER
ATTENTION: OMI/Mr. William Bush (Security)

SUBJECT: Change of Distribution Statement on AD-067003

The Defense Special Weapons Agency Security Office (OPSSI)
has approved the following report for **public release**:

AD-067003 AFSWP-797 (USNRDL-TR-35)
Measurement of Intense Beams of Thermal Radiation,
1 February 1955 by A. Broido and A. B. Willoughby.

Distribution statement "A" now applies.

Arduith Jarrett
ARDITH JARRETT
Chief, Technical Resource Center

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